Opportunistic Multihop Wireless Communications with Calibrated Channel Model

Petros Spachos , Liang Song and Dimitrios Hatzinakos
Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4, Canada

***Abstract*—Opportunistic routing schemes have been studied over the past decade to provide better performance in multihop wireless networks, by taking the advantage of the broadcasting nature of wireless channels. Simulation tools for such study are important and have been investigated to understand the network behavior. In this paper, we use real and simulated channel data to further elaborate the performance of opportunistic networks. In particular, a channel model is built by radio signal strength measurement in an indoor infrastructure, and the output of the channel model is used to feed an opportunistic network simulator. The paper then compares the performance of multihop wireless communications in opportunistic and traditional schemes.**

I. INTRODUCTION

Multihop wireless communications can have important applications in large-scale wireless networks, including wireless mesh networks and wireless sensor networks. The source and destination nodes do not have to be in the direct communication range of each other, where relay nodes in-between the source and destination can relay wireless packets in multiple hops. As such, the coverage of the wireless network can be extended without cabling. Compared to single-hop wireless networks (e.g., star-topology networks), multihop wireless networks also have higher spectrum efficiency and higher energy efficiency, since spectrum resources can be re-used over space, and less transmitting power can be used for conserving energy.

Traditional multihop wireless networking requires a predetermined network topology where routing table can be set up and a predetermined spectrum allocation where point-to-point wireless links can be configured. Both requirements are meeting challenges in engineering practice. Spectrum availability is often volatile due to co-channel interference especially in unlicensed bands; and wireless node availability can be affected by traffic congestions and other factors such as battery and hardware failures. Therefore, in traditional wireless networking, it is often encountered that the communication throughput and latency performances can degrade fast (usually exponentially) with the number of wireless hops.

Large-scale cognitive wireless networking [1] has been proposed to tackle the above challenges by an integration of opportunistic routing and opportunistic spectrum access. The performance of wireless communication in an indoor environment with a 3D-ray tracing channel model have been studied in [2]. The contribution of this paper is to compare such schemes with traditional multihop wireless networking under a realistic wireless channel model. Particularly, a channel model is builded by real measurement data in an indoor propagation environment. The model is then used for generating realistic channel parameters in OMNET++ network simulator, where performances of opportunistic and traditional wireless networks are compared. It is shown that the opportunistic can use dynamics of indoor wireless propagation where the traditional suffers from. In addition, the developed process can also be contributing to indoor wireless network planning in general.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC), and by the MRI-Ontario under an ORF-RE grant.

The rest of this paper is organized as follows. In Section II, the related works are reviewed. The channel model is described in Section III while the design and the routing protocols are presented in Section IV. In Section V, performance analysis and simulation results are presented, followed by conclusions in Section VI.

II. RELATED WORKS

The first opportunistic routing method was introduced in *Extremely Opportunistic Routing* (ExOR), [3]. Next relay node selection process in ExOR is based on a slotted acknowledge (ACK) mechanism. Whenever a node has successfully received a data packet, it has to calculate a priority level which is inversely proportional to the *expected transmission count metric* (ETX) [4]. ETX is based on the distance between the node an the destination. The shorter the distance the higher the priority. However, this simple priority criteria may lead packets toward the destination through low-quality routes. *Opportunistic Any-Path Forwarding* (OAPF) [5], overcomes this problem by introducing an *expected any-path count* (EAX) metric for a pair of nodes with a given set of candidates that captures the expected number of transmissions between them under opportunistic forwarding. According to EAX, a prioritization method for all the candidate nodes is built, which guarantees that each candidate contributes to packet delivery. Although this approach tries to calculate the near-optimal candidate set at each potential relay node to reach the destination, it needs more state information about the network and it has high computational complexity.

In ExOR, because of the simple prioritization method, duplicate packets might occur. *MAC-Independent Opportunistic routing and Encoding Protocol* (MORE), [6] introduced the concept of innovative packets. In that way it manages to avoid any duplicate packets that might occur in ExOR.

A *Geographic Random Forwarding* (GeRaF), technique was introduced in [7], [8]. In GeRaF each packet carries the location of the sender and the destination, so that the prioritization of the candidates nodes is based on location information.

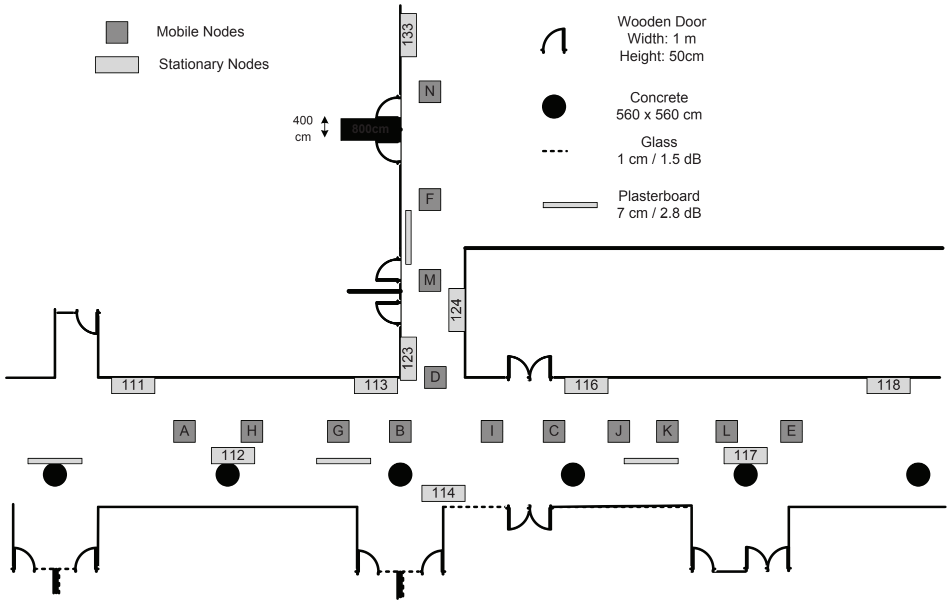

Fig. 1: Building model.

When there is no forwarder within the range of the sender node, the whole process must start over again. *Hybrid ARQ-Based Intercluster Geographic Relaying* (HARBINGER) [9] is a combination of GeRaF with hybrid automatic repeat request(ARQ). Hybrid ARQ is used for a receiver to combine the information accumulated over multiple transmissions from the same sender in order to avoid the problem when there is no forwarder within the range of the sender.

A number of other opportunistic routing protocols have been proposed [10]–[12]. *Coding-Aware Opportunistic Routing Mechanism* (CORE), [10], is an integration of localized interflow network coding and opportunistic routing. *Opportunistic Routing in Dynamic Ad Hoc Networks* (OPRAH), [11], tries to build a braid multipath set between source and destination via on-demand routing to support opportunistic forwarding.

III. CHANNEL MODELING

In this section, the approach that was followed to build the channel model is described. The channel model was build in OMNeT++, [13].

The procedure can be divided into two steps: In the first step, a number of radio nodes were distributed in a small fraction of the building. These nodes collected data for the channel in different locations of the building. In particular, the power of the signal was measured in different locations and under different materials that can affect the power of the signal such as wooden doors, concrete walls, glass windows etc.

In the second step, the floor map of the building and the location of the nodes were used to build the channel model in OMNeT++. The real data collected in the previous step, was used to build and calibrate the channel model for the specific environment.

A. Radio Nodes

OPM15 radio Nodes from OMESH Networks, [14], were used for data collection. The OPM15 radio is based on IEEE 802.15.4 standard to realize OPM (Opportunistic Mesh) dynamic networking with multi-frequency. The communication rate is $250kbps$ and the frequency band $2.4GHz$. During the measurement campaign 24 radio nodes were used.

B. Simulation Environment

The studied area is a floor of BCIT building located at the University of Toronto. Indoor environments are usually complex. The examined floor is a good example of a complex indoor environment and presents a lot of scatterers and obstacles such as walls, pillars, doors etc. These are of great influence when the radio links in such area are examined. The channel modeling has to take into consideration those objects to correctly predict the communication link availability in the area. Figure 1 shows the simulation environment.

C. Measurement Campaign

The measurement campaign covered a large part of the central corridor of the floor. For the network data collection, 24 nodes were used. During the measurements, 10 of those nodes were placed at a small fraction of a floor of a building and were used as stationary nodes. Those nodes keep broadcast during the whole measurement. The remaining 14 nodes were also placed around the stationary nodes and collect data. Each node collects data from any station node that it can listen to. The data that were collected is the power of the received signal from the different stationary nodes. The topology of the stationary nodes and the collecting nodes can be seen in Figure 1.

The measurement time was 5 minutes for each location. Received signal strength indication (RSSI) information were collected from the radio nodes and used to build the channel model. Between each communicating pair of stationary and collecting node, an average of 30 RSSI values were collected.

D. Calibration

The last step is the connection between the real measured data and the simulated data. The main goal during that step is to optimize the simulations to predict a specific metric, such as the power of the received signal as close as possible to the measured data.

Initially a simple channel model was build in OMNeT++. The simple obstacle model was used for the different wall materials. The simulation environment was described with the use of concrete walls, glass windows and wooden doors. This is the simplest description of a complex indoor environment, hence it was used as a standard channel model.

Then, the collected data from the measurement campaign was used to calibrate that model. In the initial model the description of the different materials and their impact on the communication links between the nodes is generic. After the measurement campaign and the collection of the real measured data, a more accurate description of the material and their impact on the radio communication was built. For instance, it was found that the description of the concrete wall in the simple obstacle model in OMNeT++ is not accurate enough to describe the material of the walls of the simulating environment. That description was tuned in order to provide results close to the real collected data.

Another very important aspect of the calibration procedure is the readjustment of the floor map data. The best results would be obtained by drawing accurately every piece of furniture on the map. However, a trade-off has to be found between the computation time and the complexity of the map. During the calibration procedure, the points where the real and the simulated data had great difference, more than $5dBm$, were builded again in the floor map. The main reason for great differences was usually factors that affects the signals, such as electric panels inside rooms, and can not be predicted. The measurement campaign followed by the calibration procedure helped to tuned the model in those points.

Differences between measurements and simulations as well as the calibrated model are shown in Figure 2. At nodes A, H and G, the difference between the simple model and the real data is because of the incomplete description of properties of the wall material. After calibration and proper tuning the difference is decreased. At nodes B, J, K and L the difference is because of mistakes on the floor map. Especially for node J, an electric panel in the room beside it was causing that difference.

With the calibrated model obtained, realistic simulations could be performed in the entire described area.

IV. ROUTING PROTOCOLS

In this section, the link reliability calculation is described, followed by a description of two routing protocols that was used to evaluate the differences between the channel models.

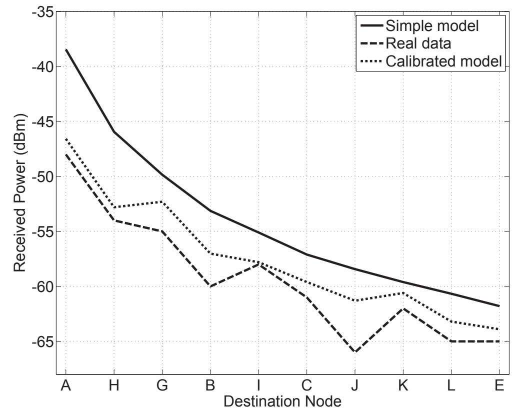

Fig. 2: Comparison between simple and calibrated channel model.

A. Link Reliability Calculation

Every node in the network can transmit packets to all the neighbor nodes in its transmission range. For every link between two nodes a Packet Error Rate (PER) has been assigned to and every packet transmission is subjected to that. If we use BPSK without channel coding, the PER for any link i between node s and node j can be written as [15],

$$PER(i) = 1 - \left(1 - Q\left(\sqrt{\frac{P_r(j)}{\sigma_n^2}}\right)\right)^{F_d}, \tag{1}$$

where $P_r(j)$ is the power of the received signal from node j, F_d is the length of the data, σ_n^2 is the noise power and

$$Q(x) = \frac{1}{\sqrt{\pi}} \cdot \int_{\frac{x}{\sqrt{2}}}^{\infty} e^{-t^2} dt.$$

B. Traditional Routing

Traditional routing has an initialization phase. During this phase, each node in the network calculates the PER for all the links with its neighbor nodes. When a node has a packet to transmit, it will try to transmit it over the most reliable link, hence the link with the smallest PER. After the initialization phase, every node keeps transmitting all the packets through the most reliable link. If a packet is lost or damaged, the node will continue trying to retransmit the packet through that link.

This approach of traditional routing enhances the reliability of the network. The PER between the transmitting nodes is small and in each time slot, packets are transmitted between neighbor nodes. In an indoor environment, such as a building, this approach will avoid retransmissions caused from lost or damaged packets, and deliver all the packets to the destination. Moreover, for traditional routing, we assume ideal scheduling, without collisions.

C. Opportunistic Routing

Opportunistic routing follows a similar approach to [16]. It uses four types of packets: Request To Send (RTS), Confirm To Send (CTS), DATA and ACK. RTS/CTS are used during the handshake process between neighbor nodes while ACKs

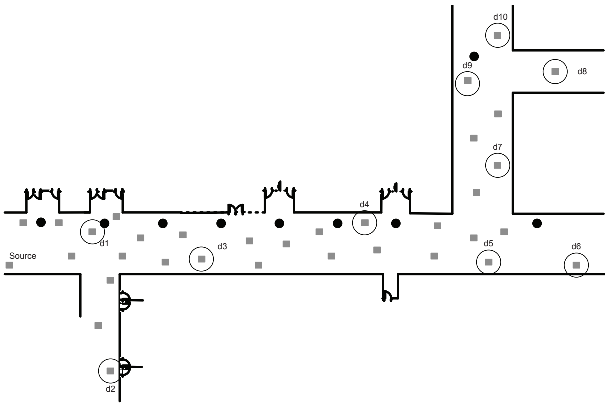

Fig. 3: Network topology.

are used for verification of DATA delivery. All the packets transmissions are subjected to PER.

Every node in the network knows its relative location and calculates a "cost of delivery" criterion. Given a node address n and the destination address d of a data packet, this "cost of delivery" $c_{n,d}$ should be locally obtained. This could indicate the average or the approximate cost of delivering a packet from the node n toward the destination d, independent of any dynamic change in the network. Usually, in large-scale wireless sensor networks $c_{n,d}$ is correlated with the distance between the two nodes.

When a node s has to transmit a packet, it first broadcasts a RTS packet, which includes its own address and the destination address, d. When a neighbor node, n, receives the RTS packet, it calculates the *cost of delivery* between the sender node and the destination, $c_{s,d}$ and compare it with the *cost of delivery* between the current node n and the destination, $c_{n,d}$.If the neighbor node is closer to the destination than the sender node, ($c_{n,d} < c_{s,d}$), node n will wait for time

$$T_{Backoff} = \frac{C_0}{c_{s,d} - c_{n,d}} + SIFS, n \neq d \tag{2}$$

where C_0 is a constant and SIFS is the smallest time interval between the RTS and CTS.

After that, the node will reply with a CTS packet.The sender node will transmit the DATA to the neighbor node that replies first with a CTS packet.

Time $T_{Backoff}$ is inverse proportional to the difference $c_{s,d} - c_{i,d}$, where i is any of the neighbor nodes. In this way, the node that is closer to the destination will try to reply first. However, because of the PER, the RTS and/or the CTS packet might get lost or damaged. In every packet transmission the sender node selects the next node dynamically according to the channel condition in that time slot. As a result, the routing path between the source and the destination is not predefined as in traditional routing but change dynamically.

V. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

In this section, we will compare traditional routing and opportunistic routing with respect to throughput and packet delay, with the use of the calibrated channel model.

We utilized simulation tools to study the performance of the proposed schemes. The network simulation was performed via the discrete event simulation system OMNeT++ with 34 nodes, with radio transmission range 10 meters. The nodes were places in different locations at the three main corridors of the floor map, at a $63 \times 63(m^2)$ network field.

We used the calibrated channel model that was build for that specific floor map. There are concrete walls, wooden walls and doors, glass and plasterboard around the floor. The infrastructure of the network area, with the nodes and the topology of the building can be seen in Figure 3.

For traditional routing we chose the most reliable link for each packet transmission, hence the link with the smallest PER. As a consequence the routing path between the source and any destination remains the same for every packet transmission. For the opportunistic routing, we consider links with PER$< 80\%$. During the simulations we had one source node and we tried different destination nodes in the network, 10 different destinations. For each pair, the simulation were conducted 10 times.

Throughput: Throughput is the number of bits divided by the time needed to transport the bits. From the source node 1000 packets were transmitted toward each destination node ,$d1 - d10$, in Figure 3. The packet size is $200bytes$ and the bit rate is $250kbps$, hence, the packet transmission time is $6.4ms$. The results can be seen in Figure 4.

During traditional routing, every packet follows the same path toward the destination. That path consists of the links with the lowest PER. In an indoor environment, such the one we examine, traditional routing follows paths around any obstacle, like plasterboard, that decreases the link reliability.

Opportunistic routing tends to find the best available and shorter path in each time slot toward the destination, leading to better throughput compared with the traditional approach. The path between the source and the destination changes dynamically in every packet transmission. The protocol tries to use links with acceptable PER that will lead to a different and shorter path than that of traditional routing.

Figure 4 shows the results for 10 different destinations. For destination 2 and 3, traditional routing performs almost the same, since both these nodes are 4 hops away from the destination. Opportunistic routing performs better than traditional routing, for the same pair of source-destination. The reason for this is because between the source and destination 3 there are more nodes than between the source and destination 2. These nodes lead to more paths and hence, increases the throughput.

Delay: Delay of a packet in the network is the time it takes the packet to reach the destination after leaving the source. The source node sends 1000 packets toward each destination, $d1 - d10$, with transmission time is $6.4ms$. The results can be seen in Figure 5.

In traditional routing every packet transmission needs exactly the DATA transmission time to be transmitted between any two nodes.

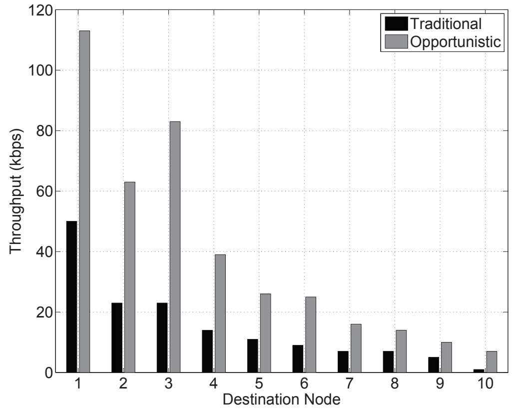

Fig. 4: Throughput in different destination from the source.

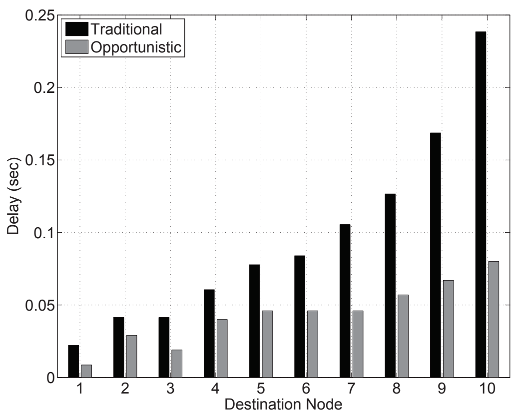

Fig. 5: Delay in different destination from the source.

Opportunistic routing needs also the RTS/CTS handshake and the $T_{Backoff}$ RTS/CTS transmission time is $0.1ms$ while $T_{Backoff}$ can be derived from Equation 2 and is inversely proportional to the distance between the sender and the receiver node.

Traditional routing utilizes the same nodes for each packet transmission. Consequent packets transmission, have to be delayed since specific nodes become available for transmission.

On the other hand,opportunistic routing transmits the packet to the best available node in each time slot, leading to a decrease of the average packet delay. Moreover, it tries to transmit to nodes closer to the destination, even if the link is not perfect, discovering shortest paths to the destination. Especially in an indoor environment, opportunistic routing tries to take advantage of any attenuation and changes the path accordingly.

Figure 5 shows the result. Following the previous approach, the delay is the same for destination 2 and destination 3, with traditional routing, while opportunistic routing performs better for destination 3. This is more clear for the delay of destination 5 and 7. Packet delay for destination 7 is higher than that for destination 5, when traditional routing is applied. Opportunistic routing takes advantage of any attenuation of the signal, for destination 7 and keeps the packet delay similar to that of destination 5.

VI. CONCLUSION

In this work, the performance of multihop routing in an indoor environment was examined. An accurate indoor channel model is adopted by considering the walls and other structural impacts . The model was further calibrated with real collected data. The final model was used in simulation of a large scale network in the area. In the examined environment, it is shown that the opportunistic routing can perform better than the upper bound of a traditional scheme, in terms of throughput and end-to-end delay.

REFERENCES

[1] L. Song and Dimitrios Hatzinakos, “Cognitive networking of large scale wireless systems,” *Int. J. Commun. Netw. Distrib. Syst.*, vol. 2, no. 4, pp. 452–475, 2009.

[2] P. Spachos, F.M. Bui, L. Song, Y. Lostanlen, and D. Hatzinakos, “Performance evaluation of wireless multihop communications for an indoor environment,” in *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, sept. 2011, pp. 1140 –1144.

[3] Sanjit Biswas and Robert Morris, “Opportunistic routing in multi-hop wireless networks,” *SIGCOMM Comput. Commun. Rev.*, vol. 34, pp. 69–74, January 2004.

[4] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris, “A high-throughput path metric for multi-hop wireless routing,” *Wirel. Netw.*, vol. 11, pp. 419–434, July 2005.

[5] Zifei Zhong, Junling Wang, Srihari Nelakuditi, and Guor-Huar Lu, “On selection of candidates for opportunistic anypath forwarding,” *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 10, pp. 1–2, October 2006.

[6] Szymon Chachulski, Szymon Chachulski, Michael Jennings, Michael Jennings, Sachin Katti, Dina Katabi, and Dina Katabi, “Trading structure for randomness in wireless opportunistic routing,” in *In Proc. of ACM SIGCOMM 2007*, 2007.

[7] Michele Zorzi and Ramesh R. Rao, “Geographic random forwarding (geraf) for ad hoc and sensor networks: Energy and latency performance,” *IEEE TRANSACTIONS ON MOBILE COMPUTING*, vol. 2, no. 4, pp. 349–348, 2003.

[8] Michele Zorzi, Ramesh R. Rao, Senior Member, and Senior Member, “Geographic random forwarding (geraf) for ad hoc and sensor networks: Multihop performance,” *IEEE Transactions on Mobile Computing*, vol. 2, pp. 337–348, 2003.

[9] Matthew C. Valenti and Bin Zhao, “Hybrid-arq based intra-cluster geographic relaying,” in *in Proc. IEEE MILCOM*, 2004.

[10] Yan Yan, Baoxian Zhang, H.T. Mouftah, and Jian Ma, “Practical coding-aware mechanism for opportunistic routing in wireless mesh networks,” in *Communications, 2008. ICC ’08. IEEE International Conference on*, may 2008, pp. 2871 –2876.

[11] Cedric Westphal, “Opportunistic routing in dynamic ad hoc networks: the oprah protocol,” in *Mobile Adhoc and Sensor Systems (MASS), 2006 IEEE International Conference on*, oct. 2006, pp. 570 –573.

[12] Haitao Liu, Baoxian Zhang, H. Mouftah, Xiaojun Shen, and Jian Ma, “Opportunistic routing for wireless ad hoc and sensor networks: Present and future directions,” *Communications Magazine, IEEE*, vol. 47, no. 12, pp. 103 –109, dec. 2009.

[13] OMNeT++ discrete event simulator, “http://www.omnetpp.org,” .

[14] OMESH Networks Inc, “http://www.omeshnet.com/omesh/,” .

[15] J.G. Proakis, *Digital Communication*, McGraw-Hill Inc., 1995.

[16] P. Spachos L. Song and D. Hatzinakos, “Performance comparison of opportunistic routing schemes in wireless sensor networks,” in *Communication Networks and Services Research Conference, 2011. CNSR ’11. Ninth Annual*, may 2011.